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Environmental and economic analysis of power generation in a thermophilic biogas plant

D. Ruiz [a], G. San Miguel [a,*], B. Corona [a], A. Gaitero [b], A. Domínguez [c]

[a] Department of Chemical and Environmental Engineering, Industrial Engineering Faculty (ETSII), Universidad Politécnica of Madrid, José Gutiérrez Abascal 2, 28006 Madrid, Spain
[b] Biogas Fuel Cell S.A., Parque Científico Tecnológico, Ada Byron 107, 33203 Gijón, Spain
[c] Purines Almazán S.L., Carretera de Gómara, Km 2.8, 42200 Almazán. Spain

HIGHLIGHTS

- Life cycle assessment, life cycle costing and cost benefit analysis were performed.
- Operation and maintenance of the biogas plant are the most impacting activities.
- Anaerobic digestion of biowaste results in negative values for climate change.
- Income obtained from waste treatment is the main input to the plant profitability.

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ABSTRACT

This paper investigates the environmental and economic performance of the power production from biogas using Life Cycle Assessment, Life Cycle Costing and Cost Benefit Analysis methodologies. The analysis is based on a commercial thermophilic biogas plant located in Spain where is installed a Combined Heat and Power system that produces electricity that is sold to the grid. Power generation has been assumed as the only function of the biogas system, expanding the system boundaries to include the additional function related to the end-of-life management of the biowastes. Thus environmental burdens from the conventional management of residues were calculated separately and subtracted. The base scenario involves using agri-food waste, sewage sludge and pig/cow manure as substrates. This situation is compared against an alternative scenario where the production of synthetic fertilizer is surrogated by the digestate.

The results have shown that the most impacting activities in all impacts categories of power production are primarily attributable to the operation and maintenance of the biogas plant except for water resource depletion and climate change. The avoided emissions associated with the conventional management of pig/cow manure more than offset GHG emissions of the biogas system resulting in a negative impact value of −73.9 g CO_2 eq/kWh in the base case scenario. The normalized results show that local impact categories such as primarily human toxicity, fresh water ecotoxicity and particulate matter are the most significantly affected by the biogas system while global impact categories as climate change and ozone depletion are less severely affected.

The operation and maintenance phase is also shown to be the largest contributor after the life cycle cost analysis, followed by the construction and dismantling of the biogas plant and the profitability of the project is primarily related to the income obtained from the management of the biowastes used as substrates.

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1. Introduction

The inadequate management of residues may cause serious impacts on the environment, such as water and soil contamination, air pollution and human health problems. However, wastes may also be seen as a resource for the production of new products or the generation of energy, thus contributing to the conservation of natural resources and to sustainable development. Anaerobic digestion is a mature technology widely used to transform fermentable biomass residues into a biogas consisting primarily of methane and carbon dioxide. This biogas may then be used directly for its heating value, it may be converted to electricity and heat through cogeneration (CHP) or it may be upgraded to biomethane for use as a replacement to natural gas (Da Costa Gomez, 2013; Minguela and Godoy, 2015). Hence, biogas plants fulfill two functions: first, the management of residues; and second the generation of

* Corresponding author.
E-mail address: g.sanmiguel@upm.es (G. San Miguel).

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energy. The potential of biogas is acknowledged and amply covered by the International Energy Agency in Task 37: Energy from Biogas (Bioenergy, 2008). In the European Union, 13.4 × 106 tons oil equivalent (Mtoe) of biogas and 52.3 × 106 MWh of biogas electricity were produced in 2013 (Eurobserv-ER, 2014). This represents a 10.2% growth with respect to 2012 and 28.8% when compared with 2011.

Biogas technology is not unique in its design and scale, ranging from small domestic digesters, medium size plants utilizing farming or wastewater treatment residues, to large centralized co-digestion installations (Deublein and Steinhauser, 2011). These plants typically operate using locally available fermentable feedstocks in order to minimize transportation costs (Deublein and Steinhauser, 2011; Minguela and Godoy, 2015). The most common biogas substrates include animal slurry, sewage sludge, farming and food-processing waste and domestic refuse. The use of energy crops (including maize, crucifers, grasses, etc.) is also becoming widespread in certain regions of Germany, Italy and France benefiting both from adequate climatic/soil conditions and favorable regulatory frameworks that promote the generation of renewable energies (Eurobserv-ER, 2014; Gissén et al., 2014).

Despite its renewable nature and green perception, the production and utilization of biogas generates environmental impacts that need to be adequately identified and quantified so that they may be managed accordingly. Life Cycle Assessment (LCA) is a well-established methodology widely used to assess the environmental sustainability of energy systems (Cherubini et al., 2009; San Miguel et al., 2015). Various publications have been dedicated to analyze the environmental performance of biogas systems in different locations, using different substrates and based on installations of different characteristics (Ishikawa et al., 2006; Cherubini et al., 2009; Jury et al., 2010; Adelt et al., 2011; Stucki et al., 2011; Poeschl et al., 2012a, 2012b; Rehl et al., 2012; Hahn et al., 2015; Xu et al., 2015; Hijazi et al., 2016). These investigations show significant methodological divergences regarding the definition of the Function and its Functional Unit (processed substrate mass, biogas volume, biomethane volume, power generation, heat generation), the allocation of impacts to different functions, the system boundaries (cradle to gate vs. cradle to grave), the selection of impact categories and the impact assessment methodology (end point vs. midpoint). The results reported suggest that the environmental performance of biogas systems are affected primarily by the type of feedstock, with significantly higher impacts associated with the use of energy crops (Adelt et al., 2011; Hahn et al., 2015; Jury et al., 2010; Poeschl et al., 2012a, 2012b) and lower for substrates of a residual nature (Ishikawa et al., 2006; Xu et al., 2015). Emissions associated with the storage of substrates and digestates have been reported to have a notable effect primarily on the climate change, toxicity and acidification categories, thus being recommended the use of devices to collect diffuse biogas emissions and the installation of gas flares. All these impacts may also be reduced by improving energy efficiency in the biogas plant and in the auxiliary elements (CHP, boiler, biogas upgrading, etc.) and also by considering the use of digestate as fertilizers (Hahn et al., 2015; Hijazi et al., 2016).

Evaluating sustainability requires going beyond the conventional environmental LCA and incorporating into the analysis economic and social performance indicators (UNEP, 2011). Life cycle costing (LCC) is a management tool employed to quantify the monetary costs associated with the life cycle of a product or service (Dhillon, 2009; Hunkeler et al., 2008). This inventory data includes all the costs borne by the promoter throughout the life cycle of the project (including capital, operation and end-of-life expenses) and also revenues derived from the selling of products or provision of services. In a biogas system, these may include the marketing of heat, electricity, provision of waste management services and also the commercialization of digestate as fertilizer. In order to take into consideration time effects, cash flows generated throughout the lifetime of the project need to be discounted to present values. LCC analysis may be expanded in complexity to take into consideration external costs (EXTERNE, 2017) or it may be supplemented with a Cost Benefit Analysis (CBA) with information about the financial attractiveness of the project. The integration of these environmental and economic evaluation tools, using the same scope and assumptions, provides a more comprehensive insight into the sustainability of the biogas system, thus enabling decision makers to consider both criteria in a coherent manner.

The objective of this paper is to produce a holistic evaluation of the environmental and economic performance of a commercial biogas plant using a life cycle approach. This has involved integrating LCA, LCC and CBA methodologies under the same scope. The analysis is based on economic and technical data from a state of the art commercial installation located in northern Spain and considers two alternative scenarios regarding the commercial use of digestate as a replacement for synthetic fertilizers.

2. Materials and methods

2.1. Goal and scope of the environmental and economic analyses

The investigation is based on a newly built biogas plant designed and constructed in Tineo (Asturias, Spain) by the Spanish engineering company Biogas Cell Fuel S.L. The installation is allowed to treat a wide range of biowaste materials using a state of the art multi-stage digestion process. Fig. 1 illustrates the different elements considered in the life cycle of the biogas system. The biowastes are transported from the point of origin to the biogas plant using tractors and trucks. Once delivered at the plant, the residues, received in liquid or semi-liquid form, are discharged into reception tanks where they are stored for no more than 48 h to avoid organic degradation and minimize greenhouse gas (GHG) and odour emissions. Reception tanks are connected to an industrial crusher where the residues are ground, mixed and homogenized prior to pasteurization at 70 °C for 1 h. The composition of the raw substrates and the mixing ratios are carefully controlled (in terms of pH, C/N ratio, % volatile solids, etc.) in order to optimize the anaerobic digestion stage.

As shown in Table 1, the digestion phase consists of two parallel lines, each one including a primary 1000 m^3 thermophilic digester operating at 55 °C followed by a secondary 975 m^3 mesophilic digester operating at 39 °C. Both reactors are based on continuous flow stirred-tank reactor (CSTR) technology and operate at hydraulic retention times (HRT) of 30 days. The two-step configuration and the long HRT ensure an effective digestion of the volatile solids and maximize biogas output. Two double membrane flexible 400 m^3 gasometers mounted on top of the mesophilic digesters are used to collect and store the resulting biogas, which is then compressed to reduce water content and subjected to biological desulphurization to reduce H_2S. The biogas feeds a combined heat and power (CHP) unit of 38% net electric efficiency and 48% thermal efficiency. Power is sold directly to the grid assuming no additional losses. The thermal energy is used onsite to heat the pasteurization process and the thermophilic digester.

The plant also has a pellet boiler for start up operations, a 420 kW security torch to burn excess methane and a bio-filter to reduce odour emissions. The digestate generated in the biogas plant is accumulated in three independent 2000 m^3 tanks from which it is collected free of charge by farmers and spread in the fields as fertilizer using drag hose technology.

The analysis described in this work is based on the biogas plant processing 26,000 t/yr of biowastes as follows: 6500 t/yr of pig slurry, 6500 t/yr of cow slurry, 7200 t/yr of sewage sludge, and 5800 t/yr of agri-food waste (comprising *animal by-products* from slaughterhouse activity and also fruit and vegetable residues). The biogas plant generates 2000 MWh/yr of power, assuming 8000 h/yr full load operation of the 250 kW CHP unit.

In practice, commercial biogas plants have two functions: i) power generation and ii) management of biowaste materials. In order to avoid partitioning and impact allocation inaccuracies in the life cycle analysis of multifunctional systems like this one, ISO 14044

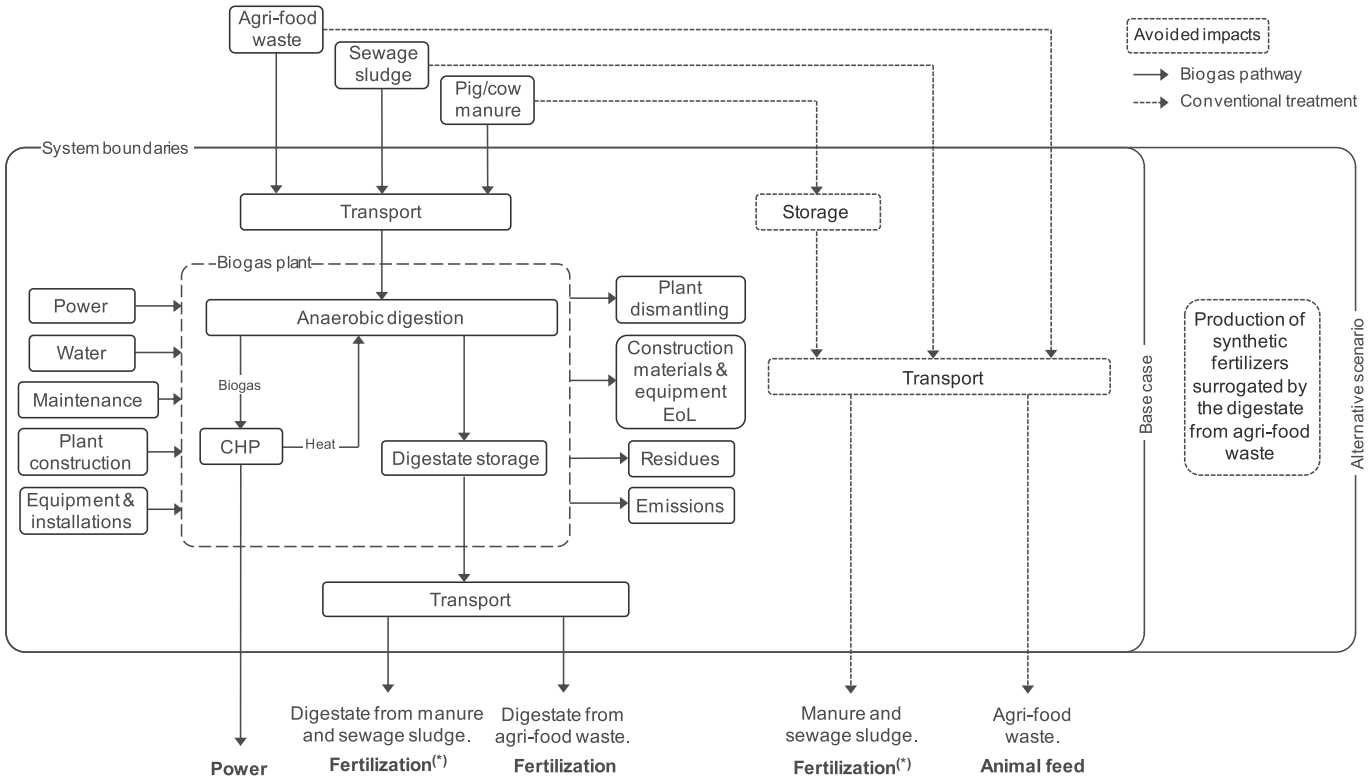

Fig. 1. Life cycle phases of electricity generation in the biogas plant.

(14044:2006) recommends the use of a system expansion approach. In application of this methodology, power generation has been assumed as the only function of the biogas system, expanding the system boundaries to include additional functions related to the end-of-life management of the biowastes (see more details in Section 2.2.4). Hence, all the impacts associated with biogas production have been attributed solely to power production while avoided environmental impacts derived from the additional functions of the biogas system have been subtracted.

In the case of pig/cow manure, the conventional end-of-life management practice involves open tank storage and field spreading as fertilizer. For sewage sludge, this involves aerobic stabilization prior to its use as a fertilizer. End of life management for agri-food wastes involves its use for animal feeding: fruit and vegetable wastes are used directly as animal fodder while the slaughterhouse residues are used to produce compound feeding stuff.

Both the Life Cycle Analysis (LCA) and the Life Cycle Cost (LCC) analysis have been structured considering the following life cycle phases: a) biowaste transport from the point of origin to the biogas plant, b) operation & maintenance, c) biogas plant and d) avoided impacts. The inventory sections below provide details about the processes considered in each of these phases.

The main objective of this investigation is to evaluate the environmental and economic implications of power generation from biogas obtained from biowastes. The Functional Unit (FU) considered in this analysis is 1 kWh injected to the grid.

Table 1
Main technical characteristics of biogas plant.

Nominal biogas production capacity (Nm^3/y)	1,300,000
Feedstock processing capacity (t/y)	26,000
Power output (MWh/y)	2000
Lifetime (years)	20
Land occupation (ha)	0.8
Thermophilic digestion (°C)	55
Mesophilic post-digestion (°C)	39
Net electric efficiency of CHP (%)	38
Thermal efficiency of CHP (%)	48

2.2. Life cycle inventory of the environmental analysis

The following sections describe the life cycle inventory of the biogas system described as *base case scenario*. An *alternative scenario* considering the use of digestate as a fertilizer is also described. This inventory data is based on real design and operating conditions, which were supplied directly from the biogas plant engineers.

2.2.1. Waste transport

As explained above, the biogas plant accepts different types of biological residues. Burden allocation for the biogas substrates was made according to the *Polluter Pays Principle* which assumes no environmental burdens for waste materials.

Table 2 shows the biowaste inputs and the assumptions employed to simulate the environmental burdens associated with transporting the different wastes to the biogas plant. Activity data was calculated taking into consideration the loading capacity of the trucks (payload) and also the utilization ratios (workload), which were determined considering the transportation capacity of the cargos and the bulk density of the wastes. For the sewage sludge and the agri-food fractions, an empty return of the trucks was assumed in the analyses. Tractors employed to transport the pig/cow manure were assumed to return with digestate. This activity data was applied to life cycle inventories from the European Life Cycle Database (ELCD 3.1), which include impacts attributable to fuel production and combustion. Emissions due to tyre abrasion, vehicle fabrication and maintenance, and construction of road

Table 2
Waste inputs and digestate outputs per functional unit of the biogas plant including type, origin and transportation requirements.

Feedstock			Transport			
Origin		kg per 1 kWh_e	Vehicle	Round trip[a] (km)	Load in departure (t)	Load in return[b] (t)
Pig manure	Livestock husbandry	3.25	Tractor	40	6	6
Cow manure		3.25	Tractor	40	6	6
Sewage sludge	Municipal waste water and from slaughterhouse	3.60	Truck, 22 t	60	14	0
Agri-food wastes	Fruit and vegetables, slaughterhouse and expired food	2.90	Truck, 40 t	120	20	0

[a] Weighted average from different origins.
[b] Digestate output for farmers.

infrastructures were also considered (Spielmann et al., 2007). Transport distances for each biogas substrate were calculated considering the location of the biowaste provider and also the mass supplied.

2.2.2. Operation and maintenance

This phase covers all the activities related to the operation and maintenance (O&M) of the biogas plant including biowaste reception and biogas production. Table 3 describes in quantitative terms the main inputs/outputs resulting from this life cycle phase, referenced to a functional unit (1 kWh). Activity data associated with the consumption of power, water and lubricants, as well as the generation of digestate and hazardous and no hazardous wastes, were quantified using a top/down approach. This involved analyzing the internal accounting system of the biogas plant. Material and energy flows were divided by the average biogas production of the plant in order to determine activity data per functional unit of product.

Power consumed onsite the biogas plant was assumed to be obtained from the grid. The electricity mix for purchased power was that of Spain in 2014 (REE, 2014). CH_4 and N_2O emissions from stored digestate in open tanks have been calculated considering the guidelines produced by the JRC (Giuntoli et al., 2014). Emission of unburnt methane in biogas fueled engines, known as methane slip, is included in the analysis assuming the conventional values reported by the JRC (Giuntoli et al., 2014).

Impacts associated with land occupation of the biogas plant (0.8 ha) have been shared by all the biogas produced throughout its lifetime. Emission factors for water, electricity and lubricant consumed in the biogas plant were obtained from Ecoinvent v3.1 database.

2.2.3. The biogas plant

This life cycle phase includes the raw materials and activities associated with the construction and decommissioning of the biogas plant, its components and also the end of life (EoL) of all the materials employed in these two stages. Table 4 provides the inventory data associated with Construction and Dismantling (C&D) activities and Table 5 describes the inventories regarding the Equipment and Machinery (E&M) employed in the biogas plant. The environmental burdens calculated for each of the elements included in these two sections have been shared by all the biogas generated during the lifetime of the plant. Life cycle inventories for construction activities, materials and equipment have been obtained from Ecoinvent v3.1 datasets.

In particular, inventory data for the manufacturing of the cogeneration unit has been adapted from Ecoinvent v3.1 datasets specific for this type of equipment. Emissions for the manufacturing of items such as stirrers or pumps have been inventoried using a generic dataset for "heavy industrial machinery" using mass as reference. The number of units considered for each of the plant components has been calculated taking into account its life expectancy and that of the plant (20 years).

2.2.4. Avoided impacts

As stated above, in the absence of the biogas plant, the biowaste materials would have followed conventional waste management routes leading to different functions and environmental burdens. A system expansion approach was applied to include in the analysis the additional functions of the biogas system. Thus, all impacts attributable to biowastes transport, operation and maintenance, and construction and dismantling of the biogas plant have been allocated to the electricity

Table 3
Inventory data associated with the operation and maintenance of the biogas plant.

I/O	Item	Use	Unit	per 1 kWh_{el}
Inputs	Energy	Purchased power	kWh	1.31E − 01
	Water		m^3	7.50E − 04
	Lubricant		kg	1.70E − 03
	Land use		m^2a	1.60E − 04
Outputs	Energy	Biogas for CHP	Nm^3	6.50E − 01
			MJ_{biogas}	1.46E + 01
		Power from CHP	kWh	1
	Digestate	Liquid	kg	1.08E + 01
		Solid		6.90E − 01
	Emissions of digestate storage from manure[a]	CH_4	kg	2.92E − 02
		N_2O		9.65E − 04
	Emissions of digestate storage from biowaste[b]	CH_4	kg	7.17E − 03
		N_2O		4.68E − 04
	Methane slip	CH_4	kg	4.72E − 03
	Hazardous waste	Lubricant	kg	1.60E − 03
		Wiping cloths		2.50E − 05
		Packaging containing contaminated residues		9.00E − 05
		Sludges containing dangerous substances		6.00E − 05
	Non hazardous waste	Paper and cardboard	kg	1.25E − 04
		Glass		1.25E − 05
		Packaging (plastic)		5.00E − 05
		MSW		1.82E − 04

[a] Pig/cow manure.
[b] Sewage sludge and agri-food waste.

Table 4
Inventory data for the Construction and Dismantling (C&D) phase of the biogas plant.

Section	Product	Amount	EoL processes
Plant construction	Concrete	2700 m^3	Dismantling, sorting plant, 25% landfill and 75% as recycled aggregates
	Precast concrete	102,000 kg	Dismantling, sorting plant, 25% landfill and 75% as recycled aggregates
	Gravel and sand	1500 kg	Dismantling, sorting plant, 25% landfill and 75% as recycled aggregates
	Structural steel	67,000 kg	5% landfill and 95% recycling
	Bitumen	1000 kg	50% incineration, energy valorization and 50% landfill
	Stone	8500 kg	Dismantling, sorting plant, 100% landfill
	Excavation	14,000 m^3	–
	Machinery	650 h	–
	Land transformation, from agriculture	8000 m^2	–
Electric installation and piping	Electric installation (wiring)	430 kg	2% landfill and 98% recycling
	HDPE piping	2400 kg	20% landfill and 80% recycling
	PVC piping	3400 kg	50% incineration, energy valorization and 50% landfill
	Copper piping	453 kg	5% landfill and 95% recycling
	Stainless steel piping	4350 kg	5% landfill and 95% recycling
	Steel Piping	11,300 kg	5% landfill and 95% recycling

generated. Environmental burdens associated with the products obtained from the conventional management of these residues were calculated separately and subtracted from those determined for the generation of biogas power.

In order to quantify the environmental burdens associated with the conventional management routes of the biowastes, two important aspects were considered: A) environmental impacts arising from the conventional management of the biowastes; B) impact savings of substituted services due to the fact that these biowastes are resources of interest for other activities. Therefore, it seems consistent that, for the biogas system expansion, substituting conventional management by the anaerobic digestion involves environmental savings from budget A, but the environmental attributions for budget B.

Emissions belonging to actions included in budget A include CH_4 and N_2O discharges caused by temporary storage of pig/cow manure in an uncovered tank before field application as fertilizer and also by transport of all biowaste materials used by conventional means. To determine these issues the following assumptions were made:

– CH_4 and N_2O emissions caused by stored pig/cow manure were calculated according to the report produced by the Joint Research Center (JRC)(Giuntoli et al., 2014). This report describes the assumptions made by the JRC when compiling default and typical GHG emissions for different solid and gaseous bioenergy pathways. The calculations made in this report are in accordance with the methodology set in COM (2010) (Commission, 2010a) and SWD (2014) 259 (Commission, 2014) in order to help economic operators to declare GHG emission savings associated with the production of electricity, heating and cooling from solid and gaseous biomass sources. COM (2010) states sustainability criteria for solid and gaseous bioenergy pathways which are similar to those reported in the Renewable Energy Directive (Commission, 2009a) and the Fuel Quality Directive (Commission, 2009b) for calculating the greenhouse impact of biofuels, bioliquids and their fossil fuels comparators.

The JRC report (Giuntoli et al., 2014) states that anaerobic digestion of manure should be considered as an improved agricultural management practice and that emissions derived from its storage must be considered as a credit to the biogas pathway. This approach is in accordance with the system expansion proposed in this investigation by the authors.

Based on IPCC Guidelines, the ratio between methane emissions caused by the storage of manure and the storage of digestate is given by the reduction of volatile solids during digestion. This implies that, with the specific conditions assumed in this study (VS reduction = 43%), the credits methane emissions from the stored manure would be equal to 1/0.57 = 1.75 times the emissions from digestate storage. Considering that methane emission from the digestate are equal to 10.0% of the methane produced at the biogas plant, the overall credits would be equal to 17.5% of the methane produced, i.e. 3.5 g CH_4/MJ biogas.

Concerning N_2O emissions, it has been considered that the proportion of ammoniacal nitrogen in the digestate is supposed to increase and that the total N is decreased due to losses in the digester, it is assumed that the net emissions from manure and digestate are equal and thus the credit would simply balance out the N_2O emissions assigned to digestate storage. Thus, N_2O avoided emission applied in this study was equal to 0.066 gN_2O/MJ biogas.

Table 5
Inventory data for the Equipment and Machinery (E&M) phase of the biogas plant.

Section	Product	Amount	Life span (years)	EoL processes
Tanks, digesters and post-digesters	Steel	36,519 kg	25	Aluminium, steel, bronze, brass and cast iron parts are recycled in 95%. Plastic parts are incinerated (energy valorisation)
	Stainless steel	37,162 kg	25	
	Glass fibre reinforcement plastic	956 kg	25	
	Rockwool	14,374 kg	25	
	Foam glass	5837 kg	25	
	Expanded polystyrene	7382 kg	25	
Stirrers		7150 kg	12	
Pumps		3970 kg	12	
Cogeneration motor		5300 kg	12	
Cooler, alternator and torch		978 kg	12	
Gasometer (Vinyl)		1608 kg	12	
Transport media	Truck, 22 tons	1 p	12	

– Transport to EoL in conventional management of biowastes (used as fertilizer and as animal feed) has been included, assuming an average distance of 25 km.

To determine emissions associated with budget B, it was taken into account that the conventional treatment of biowastes under analysis can substitute the services of: i) fertilization in the case of pig/cow manure and sewage sludge, and ii) animal feed in the case of agri-food waste (both shown in Fig. 1). Field fertilization with sewage sludge and pig/cow manure can be excluded of system expansion because the digestate from these biowastes fractions would be also applied with the same purpose in the biogas pathway. The same fertilization capacity may be assumed for both the digested and the non digested biowastes since nitrogen, phosphorus and potassium contents are not affected by the anaerobic digestion. Finally, the service given by agri-food waste fraction as animal feed has been also excluded of the system expansion due to the difficulties and uncertainties associated with defining a functional unit based on nutritional value and also the lack of information about the precise composition of this biowaste fraction. Therefore, only emissions from the budget A (avoided impacts) have been deduced and included in the system expansion of the biogas pathway.

2.2.5. Description of alternative scenario

The digestate generated by the biogas plant is returned to the environment in the form of fertilizer, which is offered to local farmers free of charge. Despite not having an economic value, the use of digestate as fertilizer may avoid the consumption of commercial fertilizers. Hence, this could be considered as an additional function of the biogas system (production of fertilizers), requiring the allocation of some of the environmental burden of the biogas system. As discussed above, allocation should be avoided as far as possible with a system expansion, deducing from the biogas system the environmental burdens associated with the surrogate fertilizers. As stated in Section 2.2.4, sewage sludge and pig/cow manure would also be used as fertilizer in the conventional management of these biowastes. Therefore, the amount of surrogate fertilizers produced by the biogas system should correspond only to the digestate fraction originated from agri-food wastes. Thus, the environmental profile of the biogas system in the base case scenario was compared with an alternative scenario where the digestate produced by the agri-food biowaste fraction is used as a surrogate fertilizer with the same amounts of nitrogen, phosphorus and potassium. In this case, aspects such as the actual amount of nitrogen available in the soil from the digestate or its mineralization to produce compounds assimilable by crops have not been taken into account. The amount of digestate produced by the agri-food waste fraction has been calculated considering its mass contribution to the total substrate inputs and the digestate outputs generated by the plant.

2.3. Methodology of the environmental analysis

The LCA was performed according to ISO 14040 and ISO 14044, and using the ILCD methodology published by the Joint Research Centre of the European Commission (EC-JRC) (Commission, 2010b) in the following categories: climate change, ozone depletion, photochemical ozone formation, particulate matter, ionizing radiation, acidification, eutrophication, human toxicity, ecotoxicity, land use and resource depletion (water, mineral, fossil and renewable). Only midpoint indicators have been calculated in this work due to the questions posed by the scientific community regarding robustness of endpoint indicators (Commission, 2010b; Sala et al., 2012). Normalisation includes the emissions and the resource extracted occurring within the EU-27 boundaries (domestic inventory) for the year 2010 (Benini et al., 2014). Cumulative Energy Demand (CED), which describes the primary energy consumed throughout the life cycle of the system, was calculated using CED v1.08 (Hischier and Weidema, 2010). SimaPro v8.1 software was used to build the models and calculations.

2.4. Life cycle inventory of the economic analysis

The economic analysis was performed considering the producer perspective. Under this assumption, the producer bears the costs associated with the construction, operation and dismantling of the biogas plant. All the costs and revenues considered in this analysis were provided by the producer. The economic inventory was organized considering the same four life cycle phases defined in the environmental LCA as follows: a) waste transport, b) operation & maintenance, c) biogas plant, and d) avoided impacts.

The waste transport phase is included in order to maintain coherence with the LCA. However, it does not involve any expenses for the producer, since it is a free service offered by the waste producers. The biogas plant phase includes construction of the biogas plant (taking place during the first year of the project) and dismantling (taking place in the last year of the project).The operation & maintenance phase takes place after the construction of the biogas plant and lasts for 20 years. It comprises costs attributable to personnel, maintenance activities (repairing, testing, cleaning…) water purchase and electricity consumption. The avoided impacts phase does not include any costs borne by the producer. However, the biogas plant benefits from public subsidies from the CLIMA Program (MAPAMA, 2017) due to carbon emissions savings attributable to the operation of the biogas plant (as compared with conventional waste management practices for the biowastes). The amount of this public subsidy is proportional to the avoided emissions and it is calculated on an annual basis, applicable to the first four years of operation of the biogas plant. The revenues from electricity sale are calculated considering an average price of 5.03 c €/kWh, according to the average annual price for 2015 published by OMIE (operator of the Iberian electricity market). Considered costs in this analysis are represented in $€_{2015}$ and summarized in Table 6.

2.5. Methodology of the economic analysis

The economic analysis performed in this study follows conventional LCC principles and was performed considering the producer perspective (Hunkeler et al., 2008). Cost items were classified into six categories and associated with the different life cycle phases of the biogas system. Table 7 shows the cost categories classification and definition. The cost

Table 6
Economic inventory for the biogas plant.

Cost items	Costs (€)
Construction of the biogas plant (civil engineering)	1,147,545
Electricity installation	98,900
Valves and piping	230,000
Plant components	1,116,300
Land purchase	311,395
Operation and maintenance costs (€/year)	
General costs (administration, management, cleaning, security)	30,000
Purchased electricity	39,420
Water	540
Personnel	92,000
Maintenance	36,000
Digestate transport	30,000
Insurance	12,000
Revenues (€/year)	
Sold electricity	100,600
Waste management income	
ABP	58,628
Residues from dairy industry	81,397
Food processing industry (and other)	18,922
Sewage sludge	167,890
Septic tanks	140,415
Public subsidies (only first four years)	50,000

was aggregated considering the time of occurrence and a constant annual inflation rate of 1.5%. This economic analysis applies a "producer perspective" where all the costs and revenues are attributable to electricity generation, without considering actual or potential uses of the waste substrates.

Net Present Value (NPV) and Internal Rate of Return (IRR) were also used as indicators of the economic viability of the biogas project (considering both waste management and electricity). For the purpose of this investigation, an equity scenario was considered where the plant is funded solely by the promoter and the capital costs are paid at the time when they are incurred.

The discount rate adopted for all internal cash flows is 7.398%. This value is the same as the "*reasonable return on investment*" for renewable energy projects susceptible for public support as adopted by the Spanish Ministry of Industry and Energy (BOE, 2014). This discount rate takes into account both opportunity costs and risk premium. IRR was calculated as the discount rate at which NPV equals zero. Monetary values were actualized using Eq. (1):

$$NPV = \sum_{t=0}^{n} \frac{Costs\ \ and\ \ revenues\ \ (real)}{(1+r)^{n}} \quad (1)$$

n = year when the expense or revenue takes placer = real discount rate (7.398%)

3. Results and discussion

3.1. Environmental analysis of biogas production: base case vs alternative scenario

Table 8 shows the impacts associated with the generation of a functional unit of the biogas system (1 kWh of electricity). The results have been obtained for the scenarios referred to as base case and alternative scenario. Twelve categories have been included in these analyses, which represent the most relevant in terms of environmental significance. The results show a negative impact value of −73.9 g CO_2 eq/kWh for the climate change category in the base case scenario. This means that avoided CO_2 and N_2O emissions associated with the storage of pig/cow manure (conventional management) more than offset GHG emissions of the biogas system. The Net Energy Ratio (NER) of the biogas system, i.e., the fraction between the net energy generated (functional unit, 1 kWh) and consumed by the biogas system (CED), is 1.081.

As shown in Table 8, the use of the digestate generated by the agri-food waste as a fertilizer represents a significant improvement in all the environmental categories of the biogas system. Thus, the negative value observed on the climate change category increases even further to −174.3 g CO_2 eq/kWh due to emissions savings associated with the use of the digestate as a surrogate fertilizer. Taking the base case scenario as a reference, reduced environmental burdens in other categories are as follows: ozone depletion (32%), human toxicity (14%), particulate matter (49%), ionizing radiation (16%), photochemical ozone formation (27%), acidification (38%), freshwater eutrophication (24%), freshwater ecotoxicity (24%), land use (60%), water resource depletion (25%) and CED (30%). The NER calculated for the alternative scenario is significantly higher at 1.545.

Table 7
Cost categories for the LCC Assessment.

Internal cost sub-categories (in €)	Description
Personnel costs	Blue-collar worker costs during operation of the power plant.
Equipment and Machinery costs	Purchase of plant components including biogas reactors, pre-treatment installations, cogeneration system, biogas upgrading, electricity installations, valves, piping and pumps.
Construction costs	Costs associated with construction and dismantling of the biogas plant. and machinery.
Land costs	Land acquirement
Water and electricity costs	Expenses relating to electricity and water purchase.
Maintenance	Costs related to maintenance of plant components and equipment
Management costs	General Expenses during operation of the biogas plant: Administration, management, cleaning, security, transport.
Revenues	Revenues associated with electricity sales, waste management fees charged by plant operator and public subsidies. This category also includes taxes.

Table 8
Characterized impacts and CED associated with the production of 1 kWh of electricity in the biogas plant.

	Units	Base case	Alternative scenario
Climate change	kg CO_2 eq	−7.39E − 02	−1.74E − 01
Ozone depletion	kg CFC-11 eq	2.23E − 08	1.51E − 08
Human toxicity	CTUh	2.51E − 07	2.15E − 07
Particulate matter	kg PM2.5 eq	1.65E − 04	8.42E − 05
Ionizing radiation	kBq U_{235} eq	4.30E − 02	3.64E − 02
Photochemical ozone formation	kg NMVOC eq	1.03E − 03	7.51E − 04
Acidification	molc H^+ eq	2.12E − 03	1.32E − 03
Freshwater eutrophication	kg P eq	1.25E − 04	9.56E − 05
Freshwater ecotoxicity	CTUe	4.28E + 00	3.25E + 00
Land use	kg C deficit	5.39E − 01	2.16E − 01
Water resource depletion	m^3 water eq	1.14E − 03	8.61E − 04
CED	MJ	3.33E + 00	2.33E + 00

Fig. 2 shows the contribution of each one of the four life cycle phases considered in this analysis (waste transport, operation & maintenance, biogas plant and avoided impacts) to the environmental impacts selected for base case scenario. The graph shows that the most impacting phase in all impacts categories is operation & maintenance, except for water resource depletion (whose main contribution is attributable to the waste transport phase) and climate change (due to avoided impacts). The second most important contribution relates to the waste transport phase on the impacts categories of CED (23.8%), land use (21.7%), acidification (14.2%), particulate matter (22.6%) and ozone depletion (11.5%). The life cycle phase identified as biogas plant has a lower significance in the impacts categories of freshwater ecotoxicity (15.6%), freshwater eutrophication (7.5%), ionizing radiation (6.2%) and human toxicity (14.3%). The avoided impacts phase is the most relevant not only in the climate change category (52.5%) but also in water depletion (33.3%) and photochemical ozone formation (23.9%).

Being operation & maintenance (O&M) the life cycle phase contributing the most to the environmental performance of the biogas system, a detailed analysis of this phase has been carried out. Fig. 3 shows the contribution of different emission sources to the O&M phase of the base case scenario. The results show that impact on the climate change category is mainly due to digestate storage (51.1%) and methane slip (20.3%). Purchased electricity, biogas combustion and internal transport contribute with 10.5%, 9.3% and 7.6% respectively. For CED, the main contributions are the energy consumed for the production of purchased electricity (62.2%) and for internal transport (31.3%). The impact categories of water resource depletion and land use are affected mainly by direct water consumption and occupied surface area of biogas plant (87% and 43% respectively). For the rest of impact categories, the most important sources of environmental burdens are related to biogas combustion, purchased electricity and internal transport.

Biogas combustion generates 79.2% of the impact associated with the freshwater eutrophication category, 78.1% of freshwater ecotoxicity, 50.4% of acidification, 33.7% for particulate matter, 33.1% of photochemical ozone formation, 31.0% of human toxicity, 11.0% for ozone depletion and 9.3% for climate change.

Purchased electricity is the main contributor to emissions in the ionizing radiation category within the operation & maintenance phase

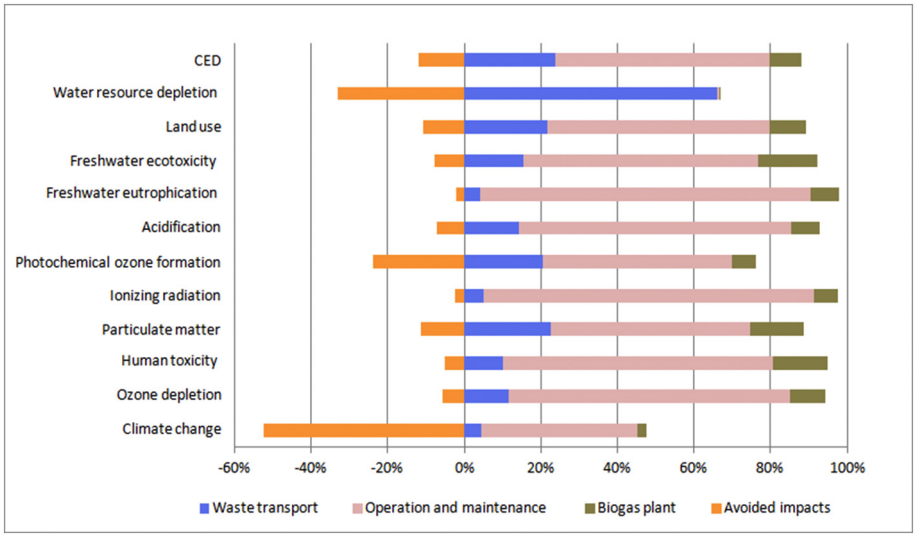

Fig. 2. Contribution of different life cycle phases to the characterized impacts of the biogas plant (base case scenario).

(88.7%) and has important weight on ozone depletion (49.7%), acidification (24.8%), particulate matter (23.9%) and photochemical ozone formation (19.2%).

Internal transport has a significant contribution to the operation & maintenance phase in the cases of human toxicity (63.9%), particulate matter (39.2%), photochemical ozone formation (35.2%), ozone depletion (28.6%) and acidification (22.8%). For freshwater ecotoxicity, freshwater eutrophication and ionizing radiation the contribution of purchased electricity and internal transport is lower than 14%.

Fig. 4 illustrates the normalized and weighted impact values for the two scenarios considered in this investigation and also the contribution of each of the impact categories considered. The impact category most significantly affected in normalized terms in both scenarios is, by far, human toxicity. The second most affected category is freshwater ecotoxicity followed by freshwater eutrophication. Acidification, freshwater eutrophication, photochemical ozone formation, particulate matter and ionizing radiation are comparatively less significant in all scenarios. Finally, normalized impacts in the climate change, ozone depletion, water resource depletion and land use categories are practically insignificant in both scenarios.

The normalized results in Fig. 4 illustrate that local impact categories are the most significantly affected by the biogas system (primarily human toxicity, fresh water ecotoxicity, particulate matter). In contrast, global impact categories (such as climate change and ozone depletion) are less severely affected. It is noteworthy that normalized results are highly dependent on the methodology employed (Heijungs et al., 2007), ILCD in this case, and may condition the environmental profile of the system with respect to the characterized results.

3.2. Economic analysis of the biogas production

Table 9 shows the internal costs per functional unit attributable to the biogas plant as determined by application of LCC methodology. To facilitate consistency in the comparative analysis of economic and environmental results, the life cycle phases considered in the LCC are the same as those considered in the LCA, although the waste transport

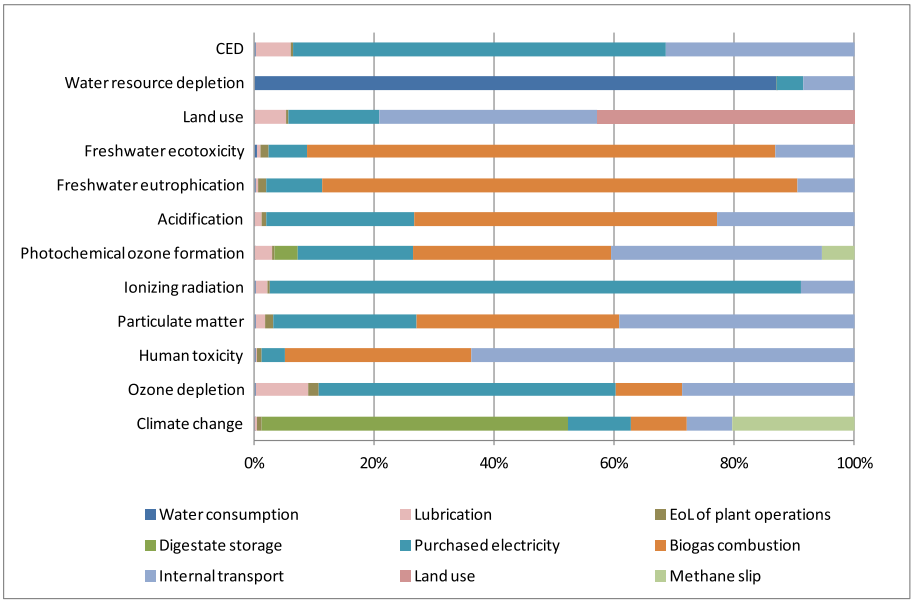

Fig. 3. Contribution of different emission sources to the Operation and Maintenance phase of the biogas plant (base case scenario).

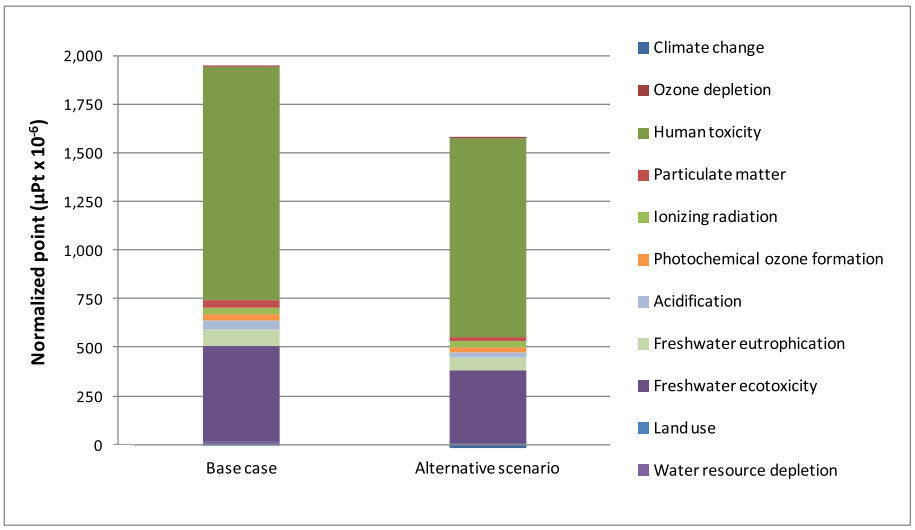

Fig. 4. Aggregated normalized and weighted impacts on different environmental categories as determined for two scenarios under study.

phase have not been assigned any costs as this is a free service offered by the waste producers. The subsidies (revenues) received by the biogas plant from the CLIMA Programme have been assigned to the Avoided impact phase.

The results show that the total life cycle costs of the biogas system amounts to 17.6 c€/kWh, with the highest contribution corresponding to the O&M phase (10.3 c€/kWh, equivalent to 58.7% of the total) due primarily to personnel (3.95 c€/kWh) and also water and electricity expenses (1.72 c€/kWh) and maintenance (1.55 c€/kWh). The life cycle stage referred to as biogas plant contributes to 7.26 c€/kWh, which represents 41.3% of all the life cycle costs of the system. The main processes in this phase are related to the purchase of Equipment and machinery (3.61 c€/kWh) followed by Construction (2.87 c€/kWh) and Land purchase costs (0.78 c€/kWh).

Total revenues amount to 22.5 c€/kWh (including corporate incoming tax), due to the gate fees charged for the management of the different organic wastes (80.7%) and electricity sales (17.4%). Subsidies from the CLIMA Programme only contribute to 2.08% of the life cycle revenues.

Fig. 5 shows the contribution of each life phase to the total costs of the biogas system in selected environmental categories. These profiles have been compared against the economic costs of the same biogas system, as determined using LCC. The environmental categories selected in this analysis were regarded as the most relevant in terms of environmental significance. Environmental savings resulting from avoiding conventional practices in the management of the biowastes due to the operation of the biogas plant are represented as negative values. These have been compared with subsidies received by the biogas plant operator from the public administration as compensation for externalities avoided by reducing greenhouse gas emissions.

Table 9
Life cycle costs associated with the production of 1 kWh of electricity in the biogas plant (1.5% inflation).

Cost categories (c€/kWh)	Waste transport	O&M	Biogas plant	Avoided impacts	Total
Personnel	0	3.95	0	0	3.95
Equipment and machinery	0	0	3.61	0	3.61
Construction	0	0	2.87	0	2.87
Land	0	0	0.78	0	0.78
Water and electricity	0	1.72	0	0	1.72
Maintenance	0	1.55	0	0	1.55
General costs and administration	0	1.29	0	0	1.29
Digestate transport	0	1.29	0	0	1.29
Insurance	0	0.52	0	0	0.52
Total costs (c€/kWh)	0	10.3	7.26	0	17.6
Revenues (c€/kWh)	0	22.5	0	0.48	23.0

As observed in the results, the environmental profile of the biogas system follows different outlines depending on the environmental category selected. Although the highest contribution lies in all impact categories (except climate change) within the O&M phase, this may vary between 86.5% in the water eutrophication category and 52.0% in particulate matter formation. Regarding climate change impacts, the environmental profile is dominated by the Avoided impacts phase due to impact savings resulting from the substitution of conventional biowaste management practices.

When comparing the economic and environmental profiles of the biogas system, some differences may be observed in the following aspects. First, the life cycle phase referred to as Biogas plant has a significantly higher contribution in the economic analysis due to the high capital costs involved in the construction of the installation. Hence, it appears that the economic costs in this phase surpass the environmental costs in relative terms. Consequently, the O&M has a proportionally lower economic significance while the contribution of the Avoided impacts phase is very limited, representing 2.7% of the total costs.

The waste transport phase does not have any repercussion in the life cycle costs. However, it represents between 4% and 24% of the total environmental impacts in the selected categories. The biogas plant phase presents higher share of economic costs (28%) than environmental impacts (2–16%).

The NPV calculation for a discount rate of 7.398%, adopted by Spain's Ministry of Industry and Energy as a *reasonable return on investment for renewable energy projects*, amounts to 474,375 €, indicating that the biogas project, in the conditions described, is economically viable. The profitability of the project is primarily related to the income obtained from the gate fees charged for the management of the biowastes, which is three times higher than the income from electricity sale. As shown in Fig. 6, the NPV of the biogas plant is largely affected by the discount rate assumed in the calculation. The Internal Rate of Return (IRR) of the biogas project, which represents the discount rate at which the NPV of all cash flows equal to zero, is 10.2%, almost three points higher than the reasonable return of investment proposed by the Spain's Ministry.

4. Conclusions

The most impacting activities in the life cycle of the biogas system are primarily attributable to the operation & maintenance of the biogas

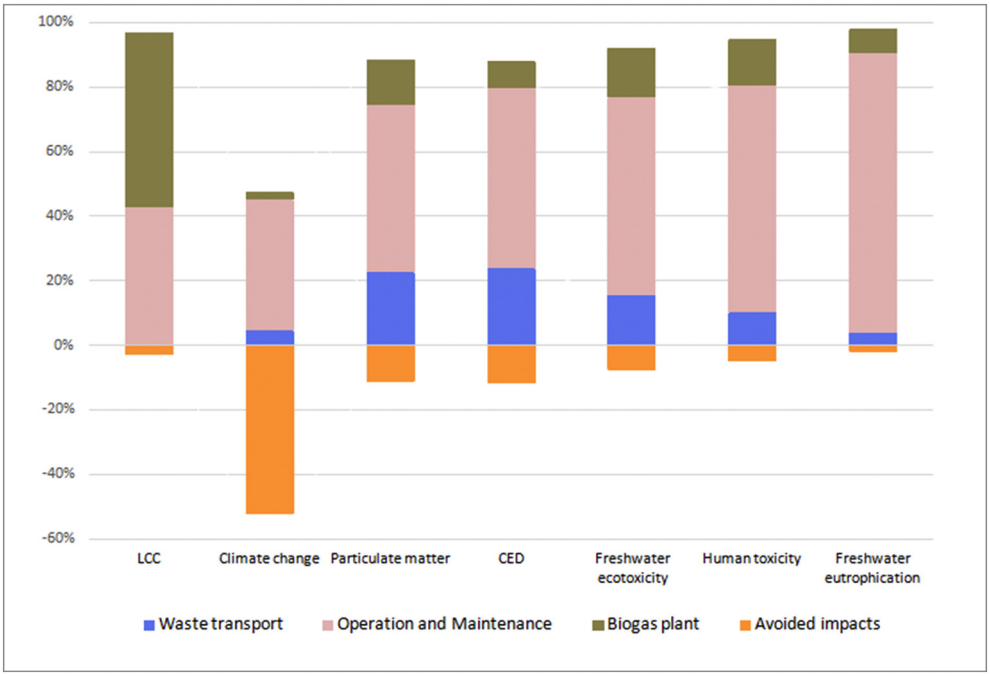

Fig. 5. Contribution of each life phase to the total life cycle costs of the biogas plant compared to the environmental contribution of selected impact categories.

plant. Excluding climate change and water resources depletion, the contribution of this phase to total impacts ranges between 49.4% for photochemical ozone formation and 86.5% for ionizing radiation and freshwater eutrophication. Among the emission sources belonging to operation & maintenance phase, the most impacting ones are biogas combustion, purchased electricity and internal transport. These sources have crucial effects on ozone depletion, human toxicity, particulate matter, ionizing radiation, photochemical ozone formation, acidification, freshwater eutrophication, freshwater ecotoxicity and CED.

Avoided impacts from the substitution of conventional treatment by anaerobic digestion have an important influence on environmental balance of biogas system. In the case of climate change, these avoided impacts offset the GHG emissions of rest of life cycle phases studied in this work.

Utilization of the digestate from agri-food waste fraction as a fertilizer improves the environmental performance of the biogas system, primarily in the human toxicity and freshwater ecotoxicity, due primarily to savings in the emission of metals in the EoL stage.

LCC analysis revealed that the life cycle phase with highest share of economic costs is the O&M phase, followed by the biogas plant (construction and dismantling). The results suggest that the relative economic benefits associated with the GHG emissions avoidance are much lower than their environmental relative repercussion. The NPV results indicated that the project is economically viable, since the IRR obtained (10.2%) is higher than the considered reasonable return on investment (7.398%). The profitability of the project is primarily related to the income obtained from the gate fees charged for the management of the biowastes. The contribution of electricity sales to the economics of the biogas system is significantly lower while the public subsidies obtained from the CLIMA Program have a negligible repercussion.

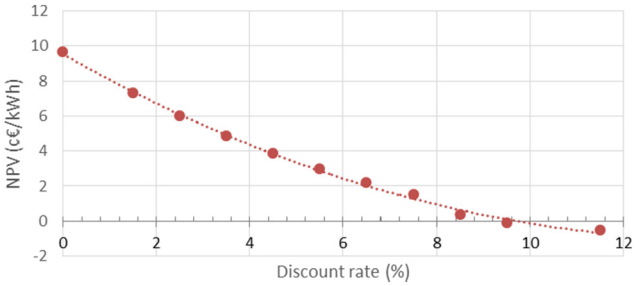

Fig. 6. NPV value for the biogas plant assuming different discount rates.

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